

The $p\bar{p}$ mass threshold structure in $\psi(3686)$ radiative decay revisited

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The near-threshold behavior of the $p\bar{p}$ invariant mass spectrum from the $\psi(3686) \rightarrow \gamma p\bar{p}$ decay reported recently by the BESIII Collaboration is analyzed. The enhancement in the $p\bar{p}$ invariant mass spectrum near threshold is nicely reproduced by the $p\bar{p}$ final-state interaction based on the isospin averaged 1S_0 partial-wave amplitude as predicted by the Jülich nucleon–antinucleon model. Contributions from the $f_2(1910)$ or $f_2(1950)$ mesons, as promoted in earlier works, are not needed.

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Recently, the BESIII Collaboration presented data with improved statistics on the $p\bar{p}$ invariant mass spectrum for the reaction $J/\psi \rightarrow \gamma p\bar{p}$, but also a first high-statistics measurement of the $\psi(3686) \rightarrow \gamma p\bar{p}$ decay [1]. The new $J/\psi \rightarrow \gamma p\bar{p}$ measurement confirmed the spectacular near-threshold enhancement in the $p\bar{p}$ invariant mass, found in an earlier experiment by the BES Collaboration [2], which has been seen as evidence for a $p\bar{p}$ bound state or baryonium [3–6], for exotic glueball states [7, 8], but also simply as manifestation of the final-state interaction (FSI) between the outgoing proton and antiproton [9–15]. A significant near-threshold enhancement of the $p\bar{p}$ invariant mass was seen also in the $\psi(3686)$ decay, although less pronounced than in the J/ψ case.

The BESIII Collaboration themselves interpreted their J/ψ decay data in terms of the $p\bar{p}$ FSI proposed by us [9], but folded with a Breit-Wigner type resonance at around 1835 MeV presuming that the structure at the $p\bar{p}$ threshold might be related to the $X(1835)$ resonance that had been observed in the reaction $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ [16, 17], see also the comments in Ref. [10]. This object is called $X(p\bar{p})$ in Ref. [17]. For the description of the $\psi(3686)$ decay the same $X(p\bar{p})$ amplitude is used but sizeable additional contributions from the $f_2(1910)$ resonance had to be invoked. Contributions of a tensor meson, but in this case of the $f_2(1950)$, were also advocated in the work of the CLEO collaboration [18], which had published data on the reaction $\psi(3686) \rightarrow \gamma p\bar{p}$ decay prior to BESIII, though with lower statistics. In both cases an isoscalar meson with a larger mass ($f_0(2100)$ and $f_2(2150)$, respectively) has been added to explain the $p\bar{p}$ spectrum at higher invariant masses.

In this report we take a closer look at those $\psi(3686) \rightarrow \gamma p\bar{p}$ data from the BESIII Collaboration. Specifically, we provide an alternative interpretation of the near-threshold enhancement solely in terms of the $p\bar{p}$ FSI, i.e. without resorting to any resonance contributions like the $f_2(1910)$ or $f_2(1950)$ (or the $X(1835)$), based on the very same $N\bar{N}$ interaction used by us previously in the explanation of the enhancement in the J/ψ decay [9].

Conservation laws for parity, charge-conjugation and total angular momentum severely restrict the partial

waves in the $p\bar{p}$ system [9] for such decay processes. Specifically, the partial-wave analysis for the J/ψ decay performed in [1] suggests that the near-threshold enhancement is dominantly in the $J^{PC} = 0^{-+}$ state, which means that the $p\bar{p}$ system should be in the 1S_0 partial wave (we use here the standard nomenclature $^{(2S+1)}L_J$ where S is the total spin and L the orbital angular momentum). However, since the decay of the J/ψ and $\psi(3686)$ to the $\gamma p\bar{p}$ system involves electromagnetic processes, isospin is not conserved so that, in principle, any combination of the isospin $I = 0$ and $I = 1$ components is allowed. Indeed, while the $p\bar{p}$ invariant mass for J/ψ decay can be understood in terms of the FSI generated by the isospin $I = 1$ component of the $N\bar{N}$ amplitude in the 1S_0 state alone – at least in our work [9] – the $I = 1$ and $I = 0$ channels can occur with different weights in case of the $\psi(3686)$ decay.

The $\psi(3686) \rightarrow \gamma p\bar{p}$ decay rate is given by [9]

$$d\Gamma = \frac{|A|^2}{2^9 \pi^5 m_\psi^2} \lambda^{1/2}(m_\psi^2, M^2, m_\gamma^2) \times \lambda^{1/2}(M^2, m_p^2, m_{\bar{p}}^2) dM d\Omega_p d\Omega_\gamma, \quad (1)$$

where the Källén function λ is defined by $\lambda(x, y, z) = ((x - y - z)^2 - 4yz)/4x$, $M \equiv M_{p\bar{p}}$ is the invariant mass of the $p\bar{p}$ system, Ω_p is the proton angle in that system, while Ω_γ is the γ angle in the $\psi(3686)$ rest frame. After averaging over the spin states and integrating over the angles, the differential decay rate is

$$\frac{d\Gamma}{dM} = \frac{(m_\psi^2 - M^2) \sqrt{M^2 - 4m_p^2}}{2^7 \pi^3 m_\psi^3} |A|^2. \quad (2)$$

The quantity A in Eqs. (1) and (2) stands for the total $\psi(3686) \rightarrow \gamma p\bar{p}$ reaction amplitude and is dimensionless.

We assume again the validity of the Watson-Migdal [19, 20] approach for the treatment of the FSI effect. It suggests that the reaction amplitude for a production and/or decay reaction that is of short-ranged nature can be factorized in terms of an elementary (basically constant) production amplitude A_0 and the $p\bar{p}$ scattering

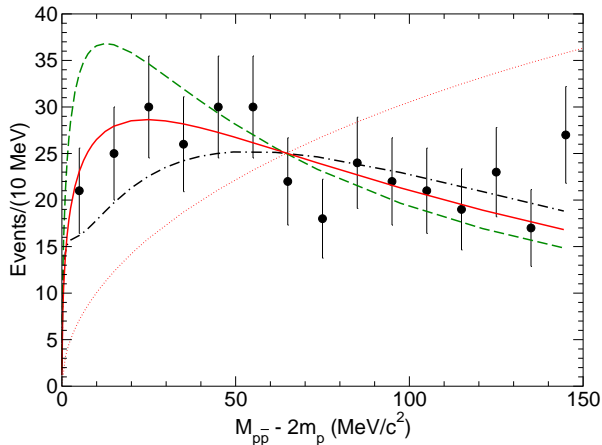


FIG. 1: The $p\bar{p}$ mass spectrum from the decay $\psi(3686) \rightarrow \gamma p\bar{p}$. The circles show experimental results of the BES Collaboration [1]. The solid line is a calculation using the $p\bar{p}$ scattering amplitude squared ($|T_{I=1} + T_{I=0}|^2$) predicted by the $N\bar{N}$ model A(OBE) [21, 22] for the 1S_0 partial wave, appropriately normalized to the data, cf. Eq. (3). The dashed (dash-dotted) curve are corresponding results using the $I = 1$ ($I = 0$) amplitudes alone while the dotted line is the spectrum obtained from Eq. (2) by assuming a constant reaction amplitude A . Those curves were normalized so that they all coincide at $M_{p\bar{p}} - 2m_p \approx 60$ MeV.

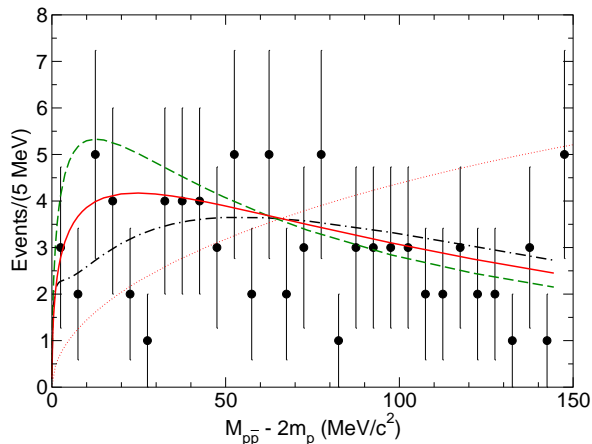


FIG. 2: The $p\bar{p}$ mass spectrum from the decay $\psi(3686) \rightarrow \gamma p\bar{p}$. The circles show experimental results of the CLEO Collaboration [18]. For notation of curves, see Fig. 1.

amplitude T of the particles in the final state so that

$$A(M_{p\bar{p}}) \approx A_0 \cdot N \cdot T(M_{p\bar{p}}), \quad (3)$$

where N is an arbitrary normalization factor, see e.g. Ref. [9] for further details. As in our investigation of the J/ψ decay we employ the amplitudes predicted by the $N\bar{N}$ model A(OBE) published in Refs. [21, 22], and we assume that the FSI effects in the $\psi(3686)$ decay are likewise dominated by the 1S_0 partial wave.

Our results are presented in Fig. 1 together with the data from Ref. [1]. As expected from the curves pre-

sented in Fig. 3 of Ref. [1], the $N\bar{N}$ amplitude in the $I = 1$ channel, which successfully describes the rather strong enhancement detected in the reaction $J/\psi \rightarrow \gamma p\bar{p}$ [9], overestimates the energy dependence seen in the $\psi(3686)$ case, cf. the dashed curve. On the other hand, the result based on the isospin averaged amplitude, $(T_{I=1} + T_{I=0})/2 \equiv T_{p\bar{p}}$, shown in Fig. 1 by the solid line, agrees rather nicely with the energy dependence found in the experiment. With an appropriately chosen normalization, cf. Eq. (3), the data are well reproduced from the $p\bar{p}$ threshold up to excess energies of about 150 MeV. In particular, the χ^2 is 8.7 for the 15 data points shown in Fig. 1 while it is 22.2, i.e. more than twice as large, for the pure $I = 1$ amplitude. We also include the result based on FSI effects due to the $p\bar{p}$ amplitude in the $I = 0$ channel alone (dash-dotted curve) and we indicate the pure phase-space behaviour by the dotted curve. The latter is obtained by using a constant amplitude A in Eq. (2). The χ^2 value for the pure $I = 0$ amplitude is 11.9. The one for the phase-space curve amounts to 60 which is a clear indication that the measured invariant mass spectrum does not exhibit a phase-space behaviour near threshold. All those curves are normalized to the solid curve at $M_{p\bar{p}} - 2m_p \approx 60$ MeV in order to facilitate a comparison of the differences in the energy dependence.

Based on those findings we do not see any need here to invoke further more substantial contributions coming from any $f_2(1910)$ or $f_2(1950)$ mesons, say, as done in Refs. [1, 18], in order to explain the data.

In Fig. 2 our results are compared with the data obtained by the CLEO Collaboration [18]. Given the poorer statistics it is difficult to infer the actual energy dependence of the $p\bar{p}$ invariant mass. Still, the solid curve corresponding to the FSI effects based on $T_{p\bar{p}} = (T_{I=1} + T_{I=0})/2$, again appropriately normalized, comes closest to the trend exhibited by the data. But in terms of the χ^2 the differences are marginal. All results including FSI effects yield $\chi^2/\text{data} \approx 20/30$ while the pure phase space amounts to 30/30.

Finally, in Fig. 3 the results for BESIII are displayed again, however this time in terms of the modulus squared of the amplitude A . Here the curves correspond directly to the (appropriately normalized) scattering amplitude squared ($|T|^2$) predicted by the $N\bar{N}$ model A(OBE) [21, 22] for the 1S_0 partial wave. The symbols indicate the experimental values of $|A|^2$, obtained from the BESIII data [1] via dividing the latter by the kinematical factors according to Eq. (2).

In summary, we have analyzed the near-threshold behavior of the $p\bar{p}$ invariant mass spectrum from the $\psi(3686) \rightarrow \gamma p\bar{p}$ decay reported recently by the BESIII Collaboration within the Watson-Migdal approach. Although in this reaction there is definitely an enhancement in the near-threshold region as compared to the phase-space behavior, it is much less pronounced than what was found for the corresponding reaction $J/\psi \rightarrow \gamma p\bar{p}$. The enhancement is nicely reproduced by the $p\bar{p}$ final-state interaction based on the isospin averaged 1S_0 partial-wave

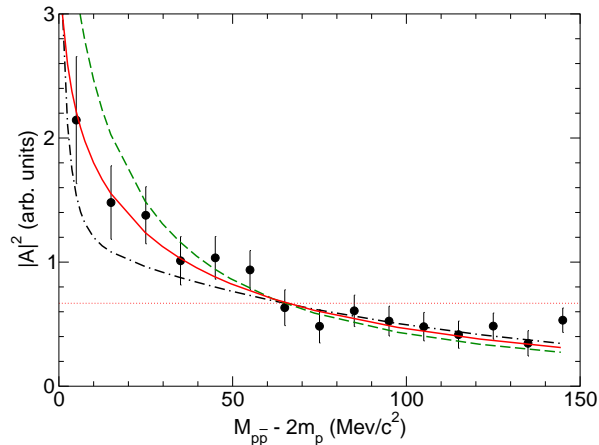


FIG. 3: Invariant $\psi(3686) \rightarrow \gamma p\bar{p}$ amplitude $|A|^2$ as a function of the $p\bar{p}$ mass. The circles symbolize the experimental values of $|A|^2$ extracted from the BES data [1] via Eq. (2). The curves are the appropriately normalized scattering amplitude squared, $|T|^2$, predicted by the NN model A(OBE) [21, 22] for the 1S_0 partial wave. For notation of curves, see Fig. 1.

amplitude as given by the Jülich NN model. In par-

ticular, any more substantial contributions from tensor mesons like $f_2(1910)$ or $f_2(1950)$, as advocated in earlier works [1, 18], are not required.

Note that we have used here the same NN amplitudes as in our study of the J/ψ decay [9]. In the J/ψ case the FSI provided by the $I = 1$ component alone led to an agreement with the measured near-threshold $p\bar{p}$ invariant mass spectrum. Clearly, the mechanisms for the decay of the J/ψ and $\psi(3686)$ mesons into $\gamma p\bar{p}$ should be different so that different admixtures of the two isospin components in the final $p\bar{p}$ state have to be expected. Only dedicated microscopic calculations, which hopefully will be performed in the future, can allow to shed light on the details of the reaction mechanisms.

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- [1] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **108**, 112003 (2012).
 - [2] J.Z. Bai *et al.*, Phys. Rev. Lett. **91**, 022001 (2003).
 - [3] A. Datta and P.J. O'Donnell, Phys. Lett. B **567**, 273 (2003).
 - [4] G. J. Ding and M. L. Yan, Phys. Rev. C **72**, 015208 (2005).
 - [5] M. Suzuki, J. Phys. G **34**, 283 (2007).
 - [6] J.-P. Dedonder, B. Loiseau, B. El-Bennich and S. Wycech, Phys. Rev. C **80**, 045207 (2009).
 - [7] C. K. Chua, W. S. Hou and S. Y. Tsai, Phys. Lett. B **544**, 139 (2002).
 - [8] J.L. Rosner, Phys. Rev. D **68**, 014004 (2003).
 - [9] A. Sibirtsev, J. Haidenbauer, S. Krewald, U.-G. Meißner and A. W. Thomas, Phys. Rev. D **71**, 054010 (2005).
 - [10] J. Haidenbauer, U.-G. Meißner and A. Sibirtsev, Phys. Rev. D **74**, 017501 (2006).
 - [11] B. Kerbikov, A. Stavinsky, and V. Fedotov, Phys. Rev. C **69**, 055205 (2004).
 - [12] D.V. Bugg, Phys. Lett. B **598**, 8 (2004).
 - [13] B.S. Zou and H.C. Chiang, Phys. Rev. D **69**, 034004 (2004).
 - [14] B. Loiseau and S. Wycech, Phys. Rev. C **72**, 011001 (2005).
 - [15] D. R. Entem and F. Fernández, Phys. Rev. D **75**, 014004 (2007).
 - [16] M. Ablikim *et al.* [BES Collaboration], Phys. Rev. Lett. **95**, 262001 (2005).
 - [17] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **106**, 072002 (2011).
 - [18] J. P. Alexander *et al.* [CLEO Collaboration], Phys. Rev. D **82**, 092002 (2010).
 - [19] K.M. Watson, Phys. Rev. **88**, 1163 (1952).
 - [20] A.B. Migdal, JETP **1**, 2 (1955).
 - [21] T. Hippchen, J. Haidenbauer, K. Holinde, V. Mull, Phys. Rev. C **44**, 1323 (1991).
 - [22] V. Mull, J. Haidenbauer, T. Hippchen, K. Holinde, Phys. Rev. C **44**, 1337 (1991).